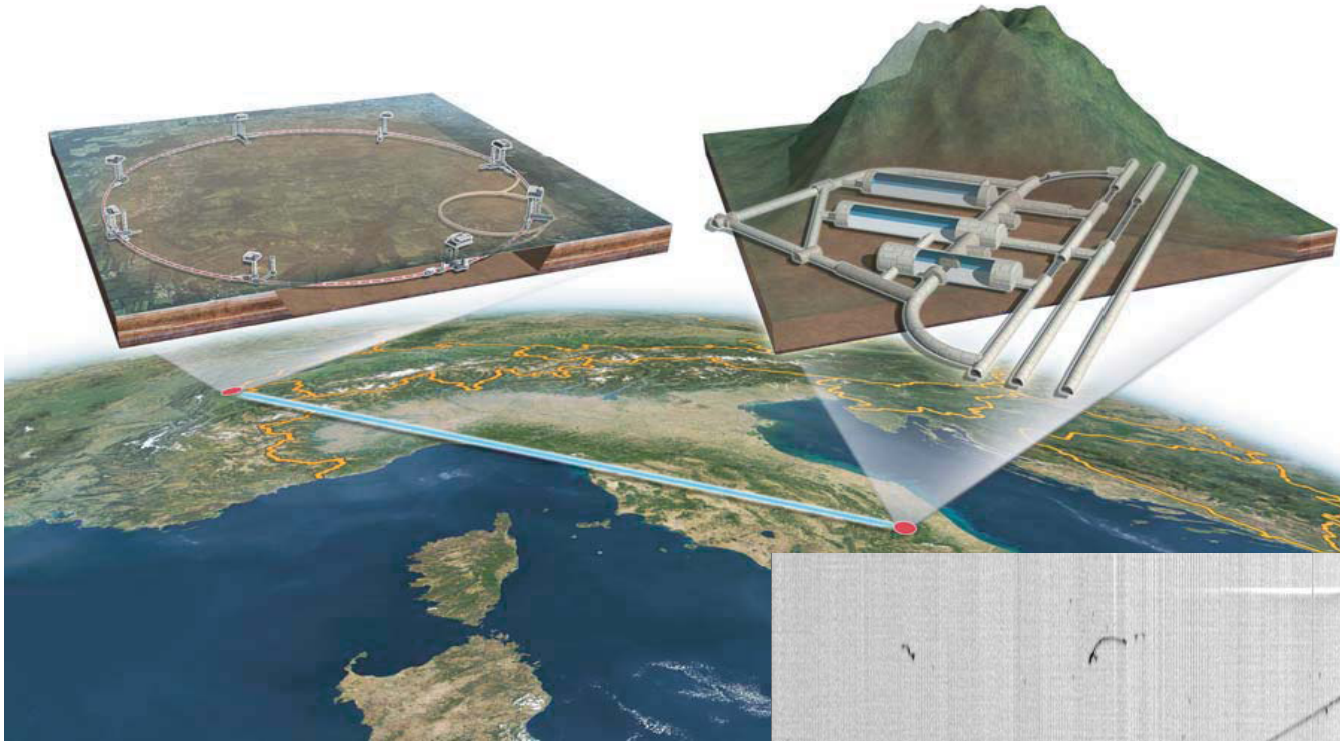


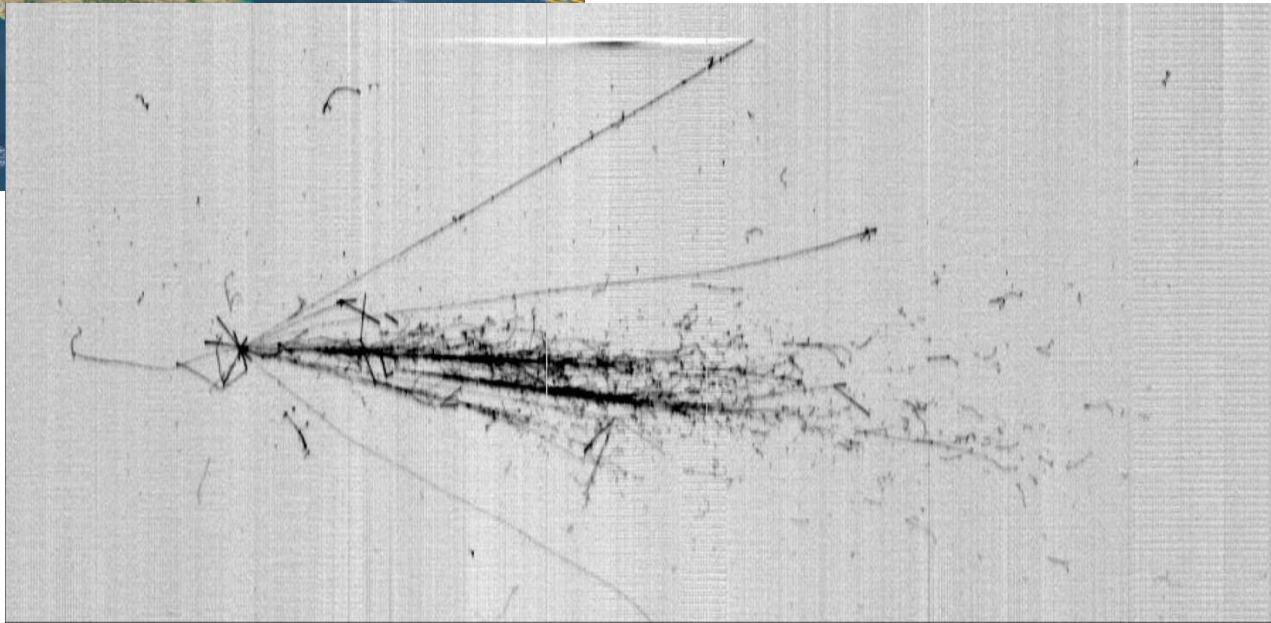
ICARUS-T600: reconstruction of events from the CNGS run

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ICARUS Collaboration



*FERMILAB
19-20 October 2015*



The ICARUS Collaboration

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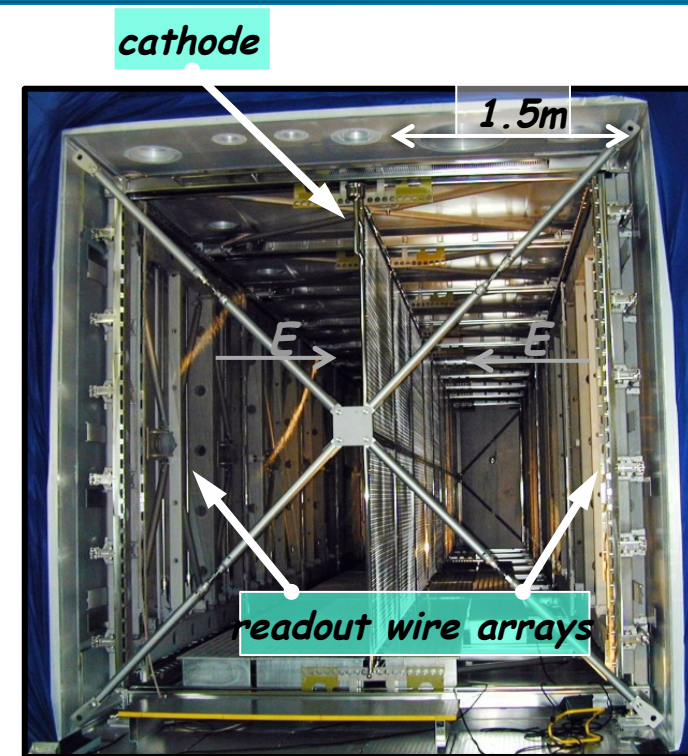
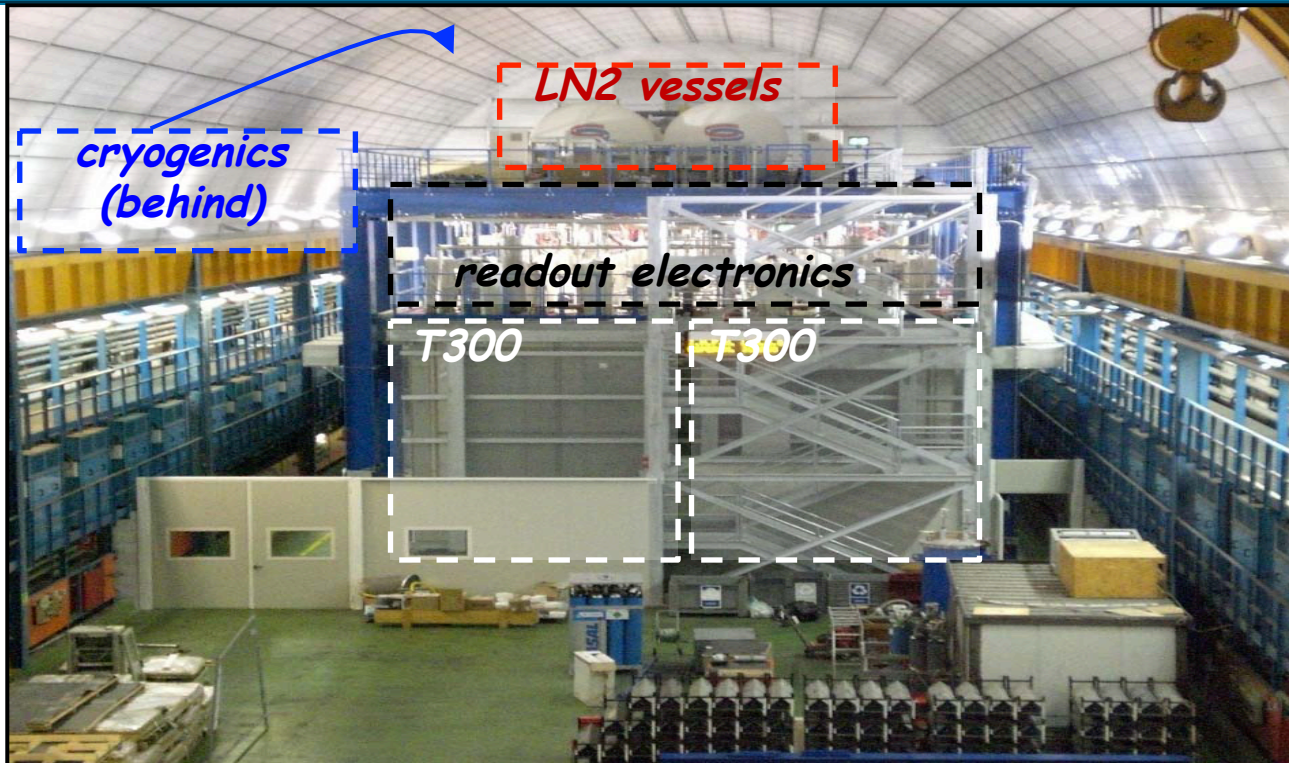
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+ ICAR-US : 6 new US groups:
Colorado Univ., Pittsburgh Univ.,
SLAC, FNAL, Argonne, Los Alamos

*Spokesperson

ICARUS-T600 at LNGS laboratory



Two identical modules

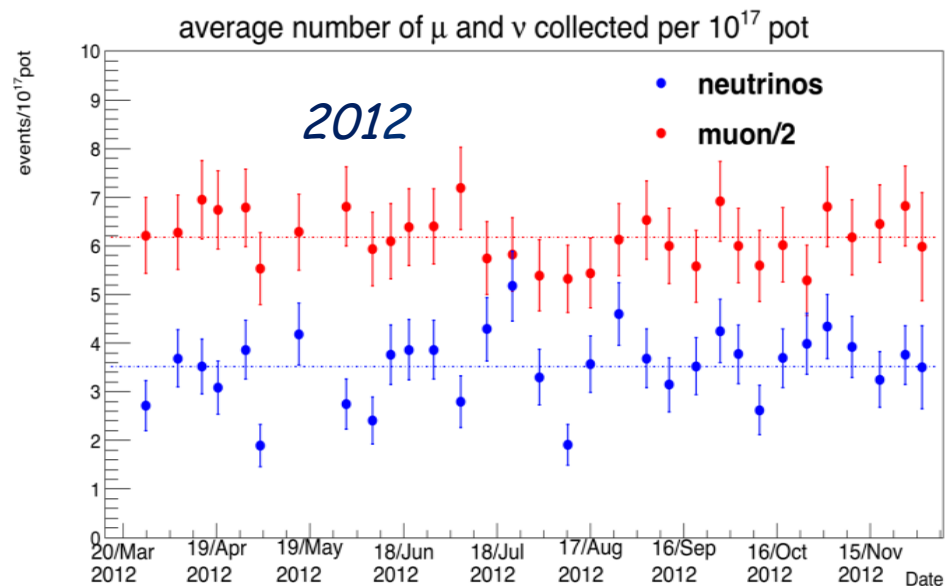
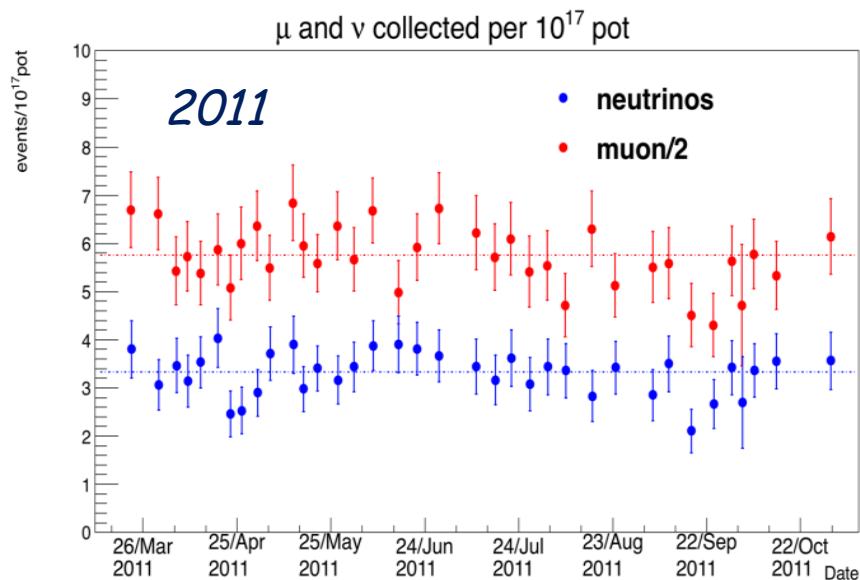
- $3.6 \times 3.9 \times 19.6 \sim 275 \text{ m}^3$ each
- LAr active mass: 476 t
- Drift length: 1.5 m (1 ms)
- $E = 0.5 \text{ kV/cm}$, $v_{\text{drift}} \sim 1.5 \text{ mm}/\mu\text{s}$
- Sampling time $0.4 \mu\text{s}$ (sub-mm resolution in drift direction)

Four wire chambers: 2 chambers/module

- 2 Induction + 1 Collection readout wire planes per chamber; ~ 54000 wires, 3 mm pitch and plane spacing, oriented at $0^\circ, \pm 60^\circ$;
- Charge measurement on last Collection plane
- 20+54 8" PMTs for scintillation light detection:
- VUV sensitive (128nm) with TPB wave shifter

ICARUS T600 results

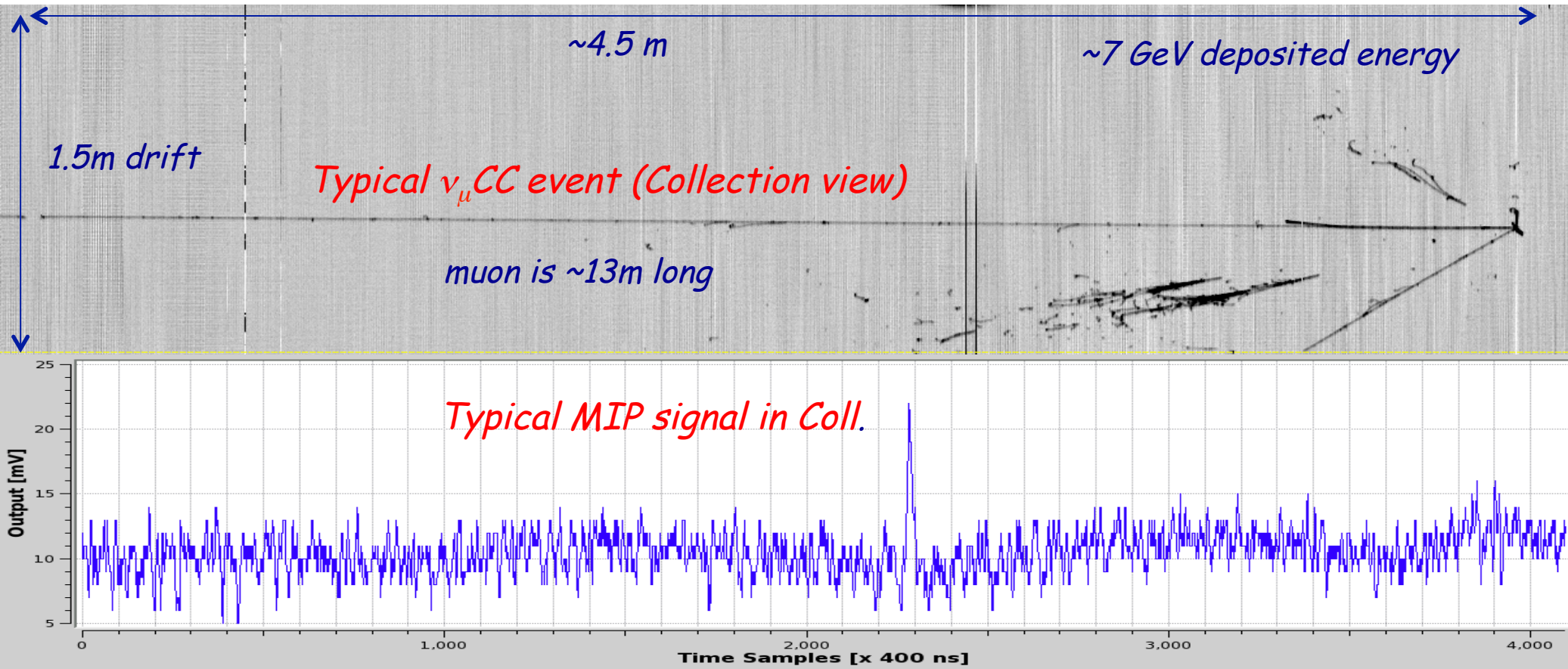
- ICARUS concluded in 2013 a very successful 3 year long run at LNGS;
- The T600 detector has been successfully exposed to CNGS beam from Oct. 1st 2010 to Dec. 3rd 2012: **$8.6 \cdot 10^{19}$ protons on target** collected with a remarkable **detector live time > 93 %** and recording **2650 CNGS neutrinos (in agreement with expectations) on $7.93 \cdot 10^{19}$ pot**
- Data taking conducted in parallel with c-rays to study atmospheric ν and p-decay (0.73 kty exposure);



- The relatively small number of recorded CNGS neutrino interaction events (~ 3000) allowed a semi automatic approach based on a pre-selection of events followed by a careful visual analysis of all physically interesting data; the reconstructed objects can be saved/modified using a flexible ROOT-based I/O system
- The developed software framework is based on:
 - Central package (fullreco) for data decoding, basic reconstruction
 - Qt-based event display (Qscan) for visualization/scanning and human interface
 - Event loop code (AnalysisLoop) for batch analyses and ROOT I/O
 - Higher-level analysis tools (Muon momentum by MCS, EM shower reconstruction, particle identification, 3D reconstruction...);
 - Interface with FLUKA for analysis/visualization of simulated events;
 - Interface with MySQL for access to DB;

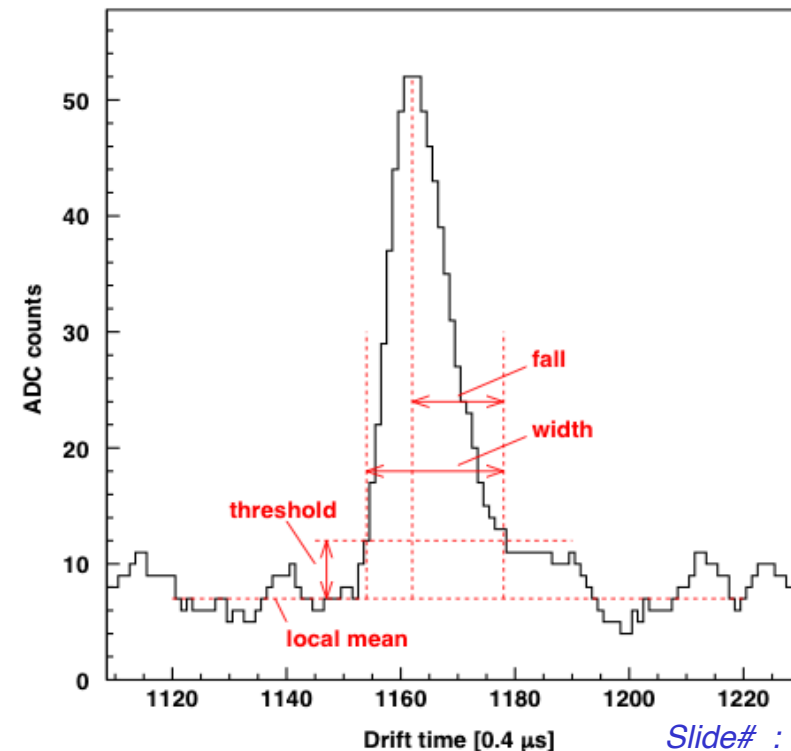
Qscan event display for the ICARUS events

- Qscan is a qt-based tool for a fast visualization of events in the T600:
 - the 2D projections associated to the wire planes are shown using a grey/color scale based on signal height/deposited energy;
 - the waveforms of wires and PMT signals can be displayed and fast Fourier transform tool available, useful for noise monitoring



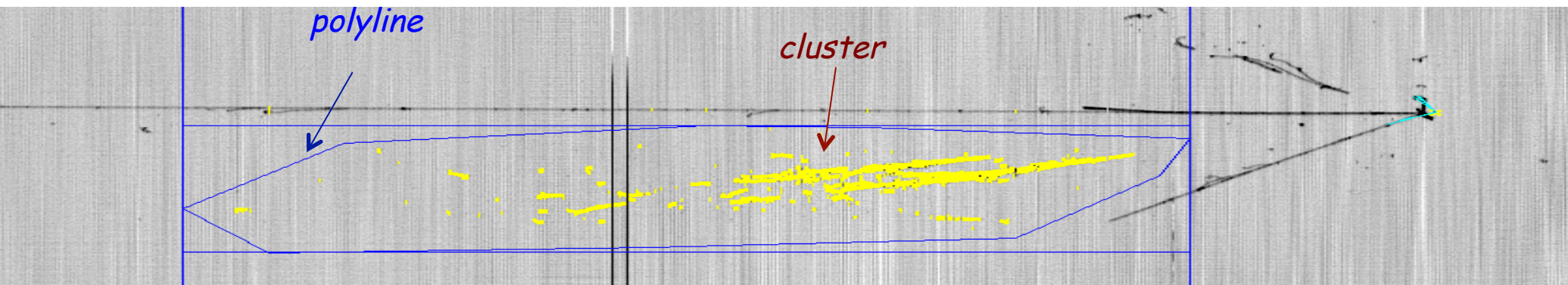
Signal reconstruction: hit finding (fullreco)

- A physical “hit” in the detector is identified as a wire signal above a defined threshold computed over local mean (baseline) for a long enough time (in order to avoid fake hits from noise spikes); threshold in Collection: 4 ADC#, typical m.i.p. signal: 15 ADC#
- Conditions on the threshold, minimum width and fall time for the hits change for the different views (Induction 1, Induction 2, Collection);
- Dedicated tools developed to filter out detector or read-out electronics effects that can worsen wires S/N ratio, degrading the capability to identify physical signals:
 - Spurious hits induced from PMT signals filtered out;
 - 100 kHz noise removed;
 - Isolated low hits removed.



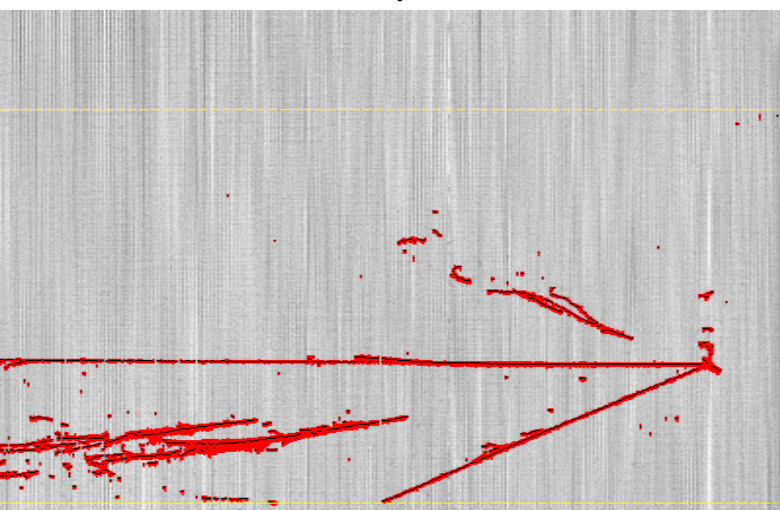
Cluster reconstruction (fullreco)

- Clusters are connected sets of hits in a 2D view corresponding to a physical particle; they can be created by:
 - An automatic algorithm developed for simple topologies (single tracks, low-multiplicity interactions): aligned and connected hits grouped and then segments are merged based on direction angle and distance between end-points;
 - A manual procedure in Qscan used by scanners for more complex topologies, typically showers: all the hits inside a polygonal line defined by the scanner are assigned to the same cluster;
- The clusters can be matched between different views as input for the 3D reconstruction; vertices and reference points can be also associated to the clusters;



Reference points and vertices

- Reference points and vertices can be defined to mark interesting features of the event in a 2D view (primary interaction, delta rays, decay point of tracks, shower features, muon begin/end point for the momentum measurement via MCS);
- They can be selected manually in Qscan and can be associated to clusters and matched between different views providing additional input to 3D reconstruction;
- An automatic tool for the primary vertex identification is available;
- Reference points and vertices can be saved in root files;



Vertex 2D Setup

Vertex Properties | Position and Links

Primary	Yes
Source class	CNGS nu
Reaction type	DIS
Reaction current	CC
Incoming particle	nu mu
Source Object	not set

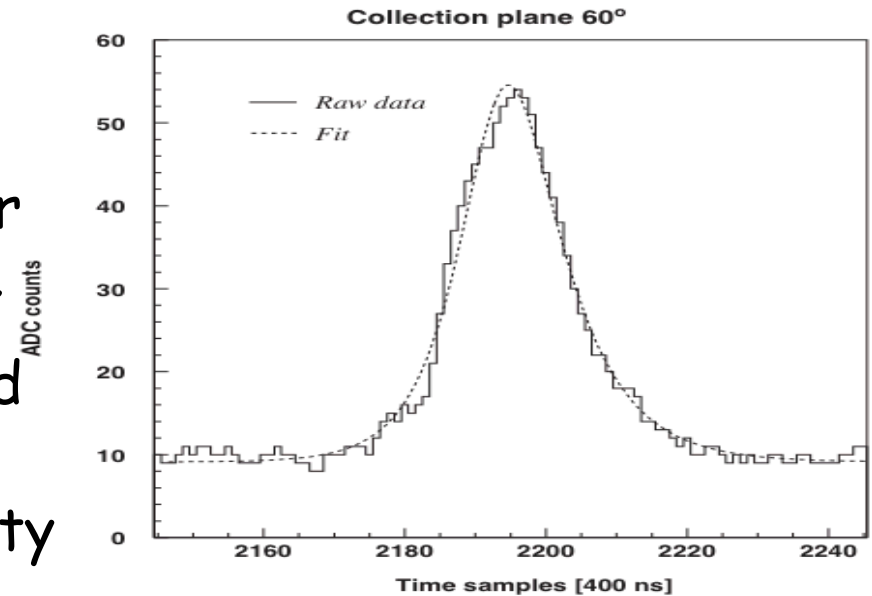
☐ Save ADC on wires

OK Cancel

Measurement of the deposited energy (fullreco)

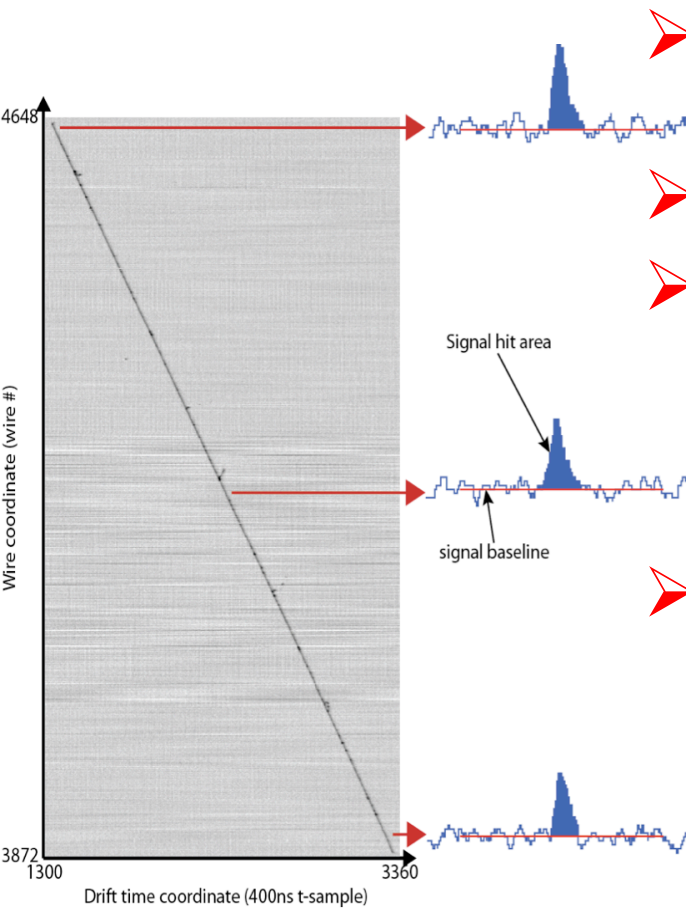
- Precise and unbiased measurement of hit area is a key point for the calorimetry since the deposited energy on each wire is proportional to integral of wire signal in Collection view
- Physical "hits" are fitted with function considering a large interval (± 70 sample around the peak) in order to obtain a precise baseline B estimation
$$f(t) = B + A \frac{e^{-(t-t_0)/\tau_1}}{1 + e^{-(t-t_0)/\tau_2}}$$

(typical $\tau_1 \sim 3\mu s$, $\tau_2 \sim 0.9\mu s$)
- Procedure for fitting overlapping hits from different close physical tracks or long hits from inclined tracks available
- Hit area is then converted in deposited energy taking into account the appropriate calibration constants, purity and quenching corrections;
 - The sum over all the hits belonging to the same clusters gives estimate of the particle deposited energy



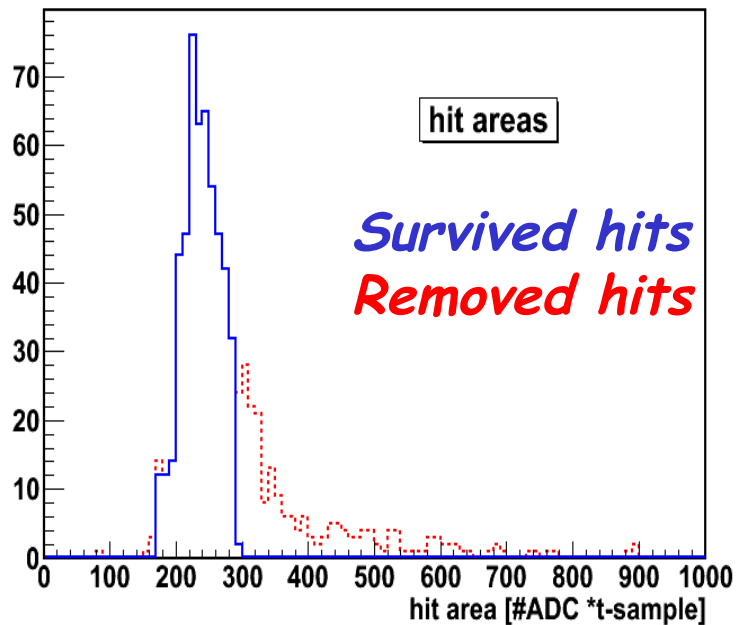
Purity measurement in ICARUS T600

- The electron lifetime τ_{ele} measurement is a key feature for a precise measurement of the deposited energy in the events; a fully automatic procedure to monitor online the attenuation $\lambda = 1/\tau_{ele}$ has been prepared for the LNGS run;
- First step: selection of through-going cosmic-ray muons

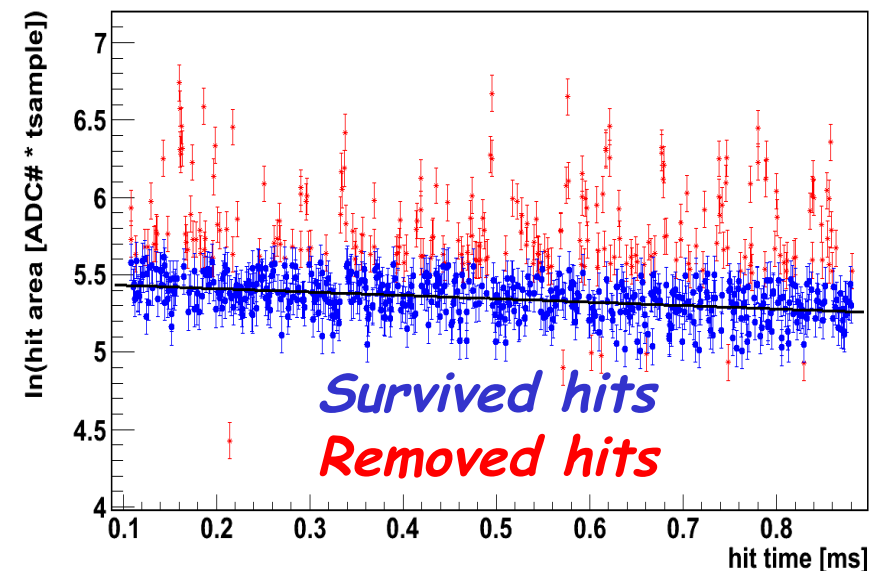


- Rejection of noisy wires to reduce "fake" hits that can mimic a physical activity inside the detector;
- Identification of the physical event region;
- Selection of events based on the number of hits in Collection view, on their relative position and energy: at least 100 wires and 1450 t-samples (400 ns each) occupied and $0.8 < N_{hits} / N_{wires} < 1.1$;
- Recursive rejection of hits at more than 3 mm distance from the track is applied: residual δ -rays along the track are removed;

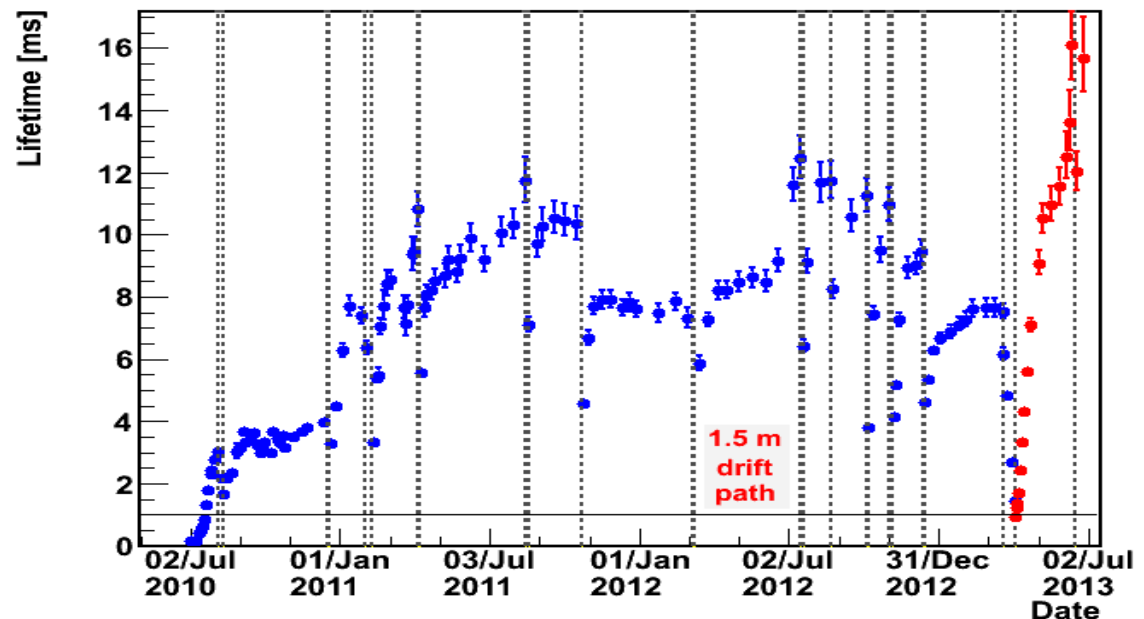
Purity measurement: method description - 2



- $\lambda = 1/\tau_{ele}$ obtained by a fit of the charge attenuation along each selected tracks after a 2 step procedure to remove the asymmetric Landau tail of the dE/dx distribution (to remove large non Gaussian fluctuations);
- The final value of $\lambda = 1/\tau_{ele}$ estimated as the average of λ_{track} on 100 tracks;

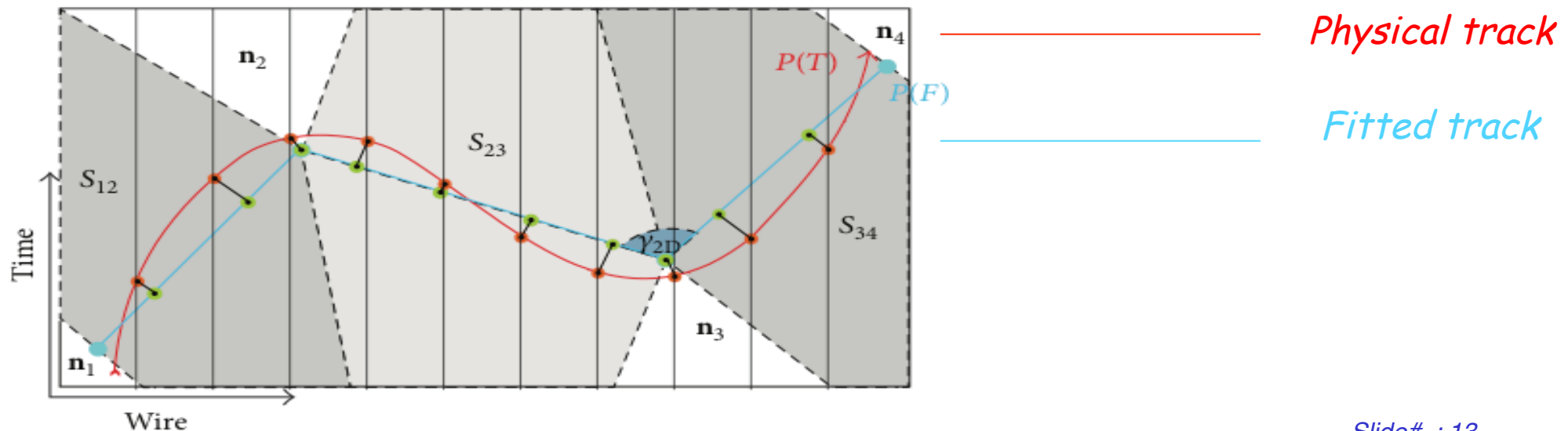


Electron lifetime trend East cryostat

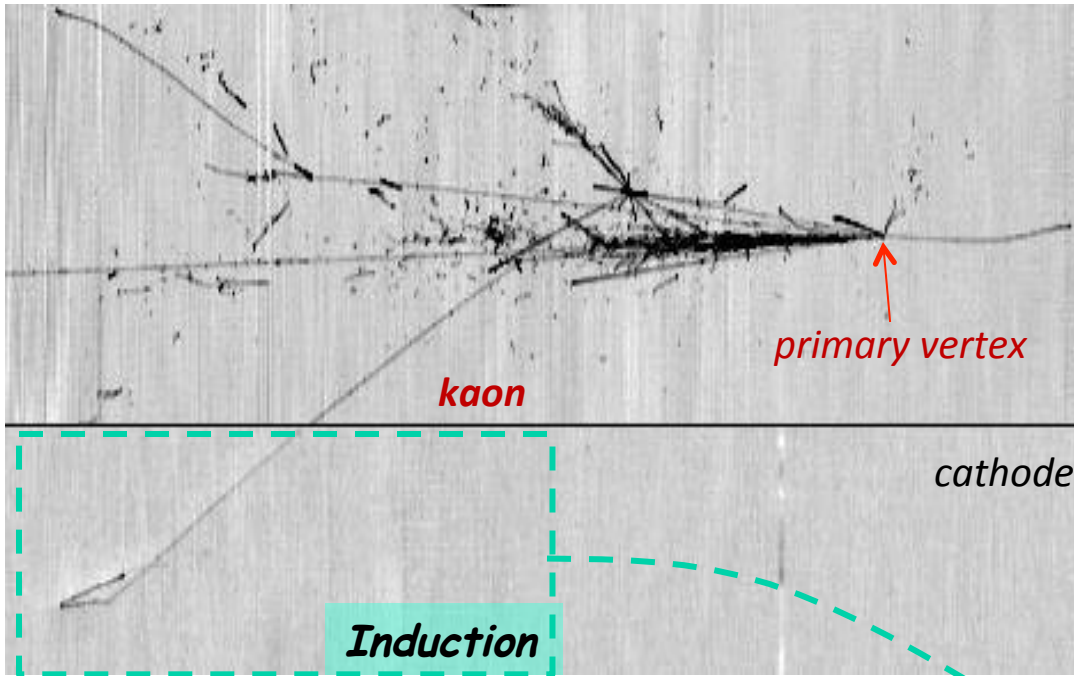


3D track reconstruction

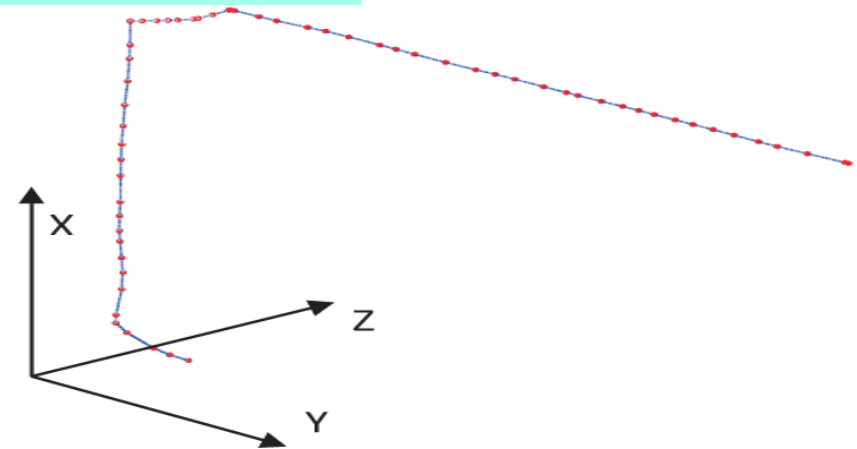
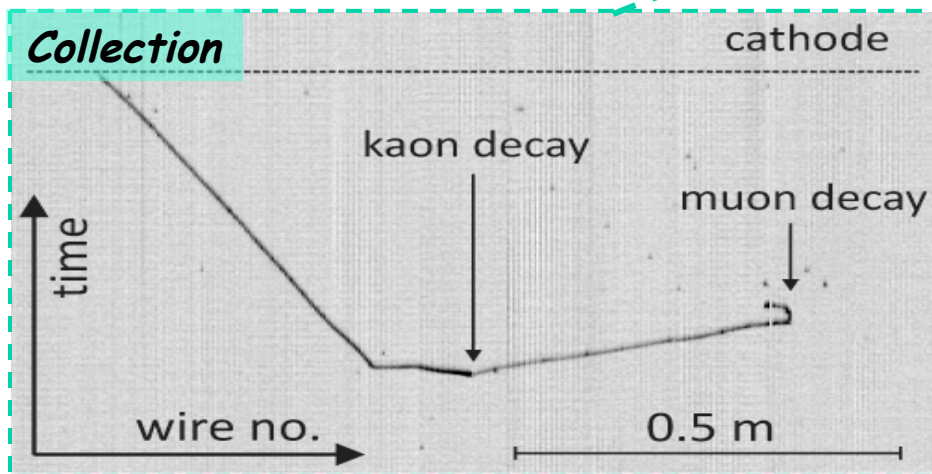
- Automatic algorithm, starting from 2D tracks in each view;
- Polygonal Line Algorithm (PLA) based on simultaneous optimization of all 2D projections to match data on wire planes;
- PLA track fit constructed iteratively introducing additional node along the track and recalculating the fitted track direction;
- Fit minimizes at each step a function G depending on the distance between the track and the fitted projection and taking into account the track curvature and the available constraint on the track;
- Iteration stops when the maximum number of nodes is reached;



3D reconstruction example



- 3D algorithm tested on single tracks and more complex topologies;
- Similar logic can be also extended to 3D vertex and shower reconstruction;

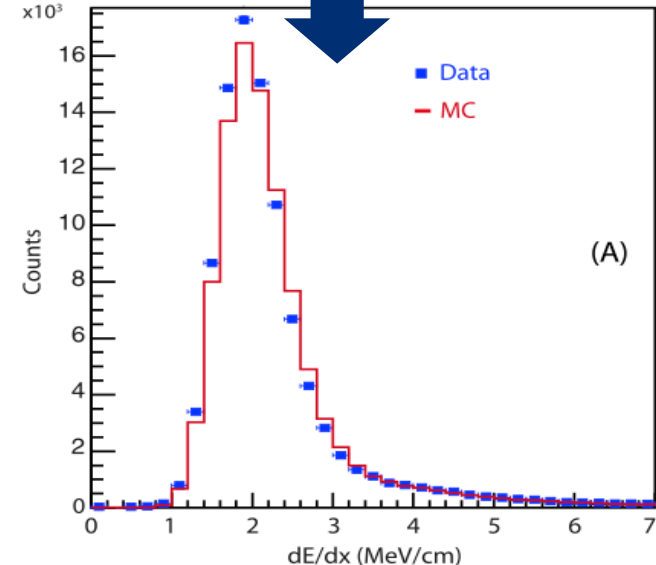
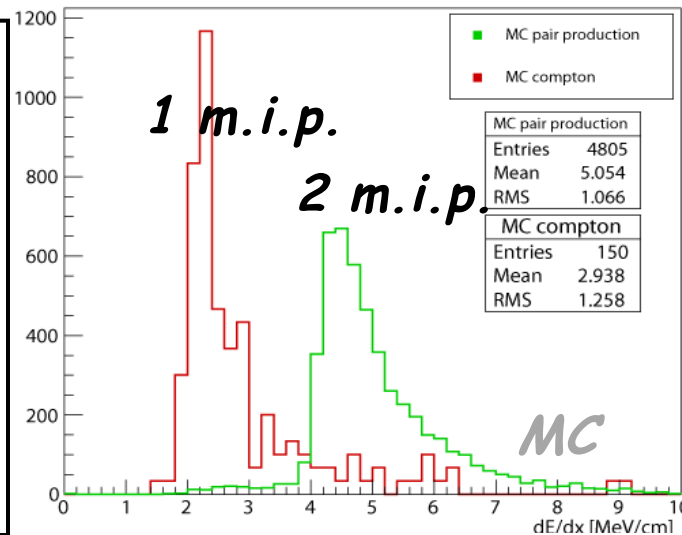
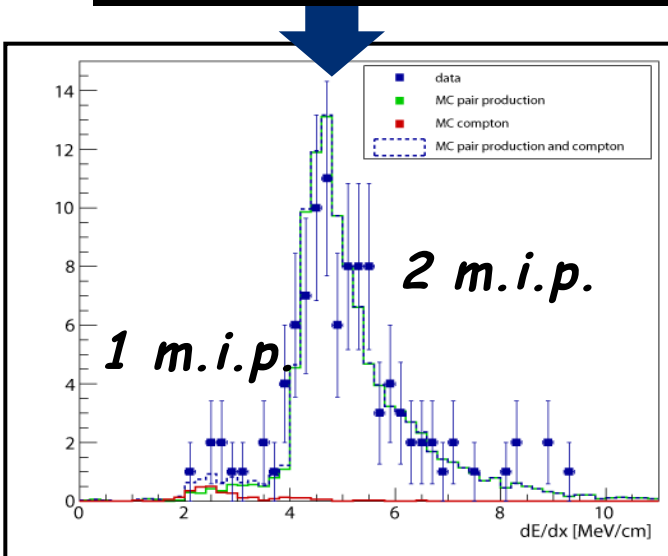


dE/dx measurement

- Calorimetry and 3D reconstruction allow accurate dE/dx measurement
- MIP ionization density distribution (Landau+Gaussian) agrees well with expectations in LAr
- Study of MIP cosmic muons has been developed to monitor possible disuniformity in detector response;
- dE/dx measurement key feature for the electron/photon separation;

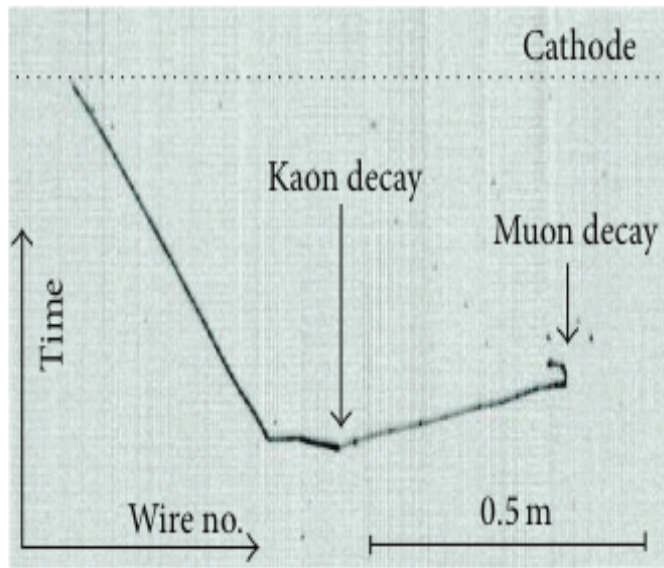
- *MC: single electrons (Compton)*
- *MC: $e^+ e^-$ pairs (γ conversions)*
- *data: EM cascades (from π^0 decays)*

Simulated and collected muon tracks from CNGS
 $\nu_\mu CC$

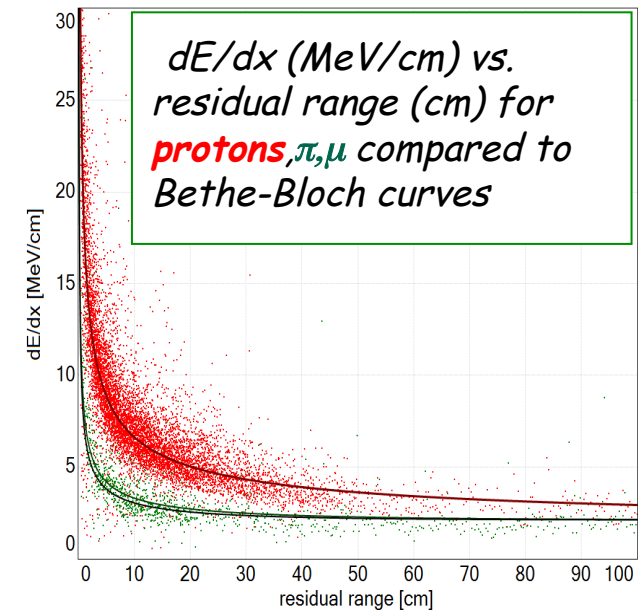
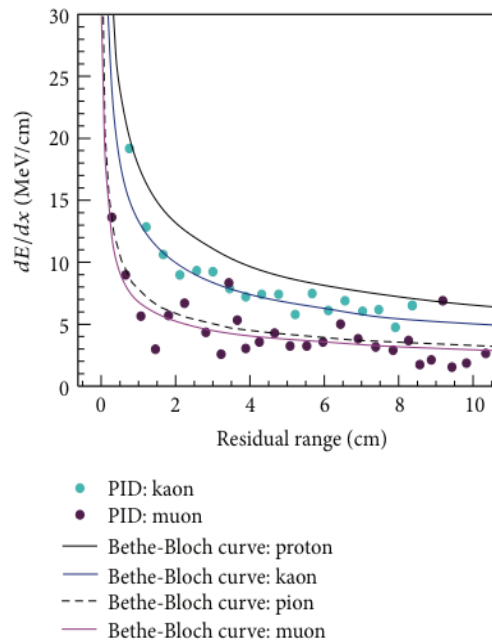


Particle identification

- Behaviour of dE/dx vs. range allows to estimate mass and identify a stopping particle track;
- Particle identification (PID) implemented on neural network;
- Pion/kaon/proton separated with high efficiency >95%
- Pion/muon separation more marginal;



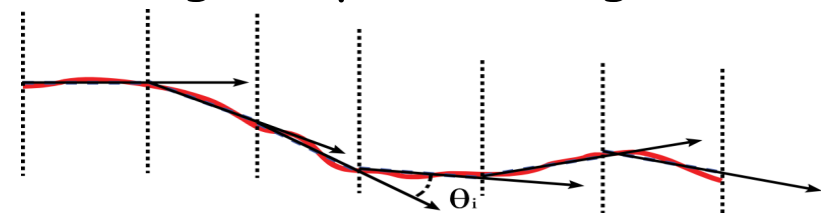
(a)



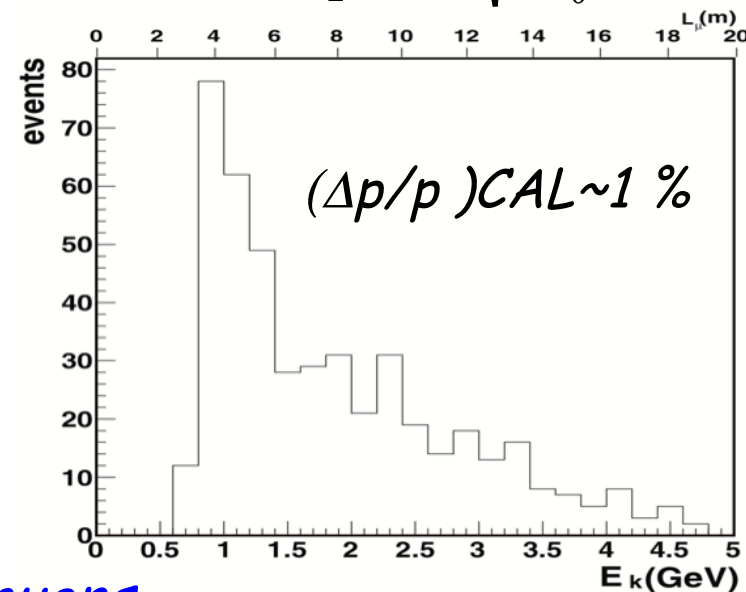
Measurement of muon momentum via multiple scattering

- Multiple Coulomb Scattering (MCS) is the only way to measure momentum of non-contained muons and so it is crucial for ν_μ CC events
- Algorithm based on evaluation of average RMS of deflection angles θ_{RMS} (Collection view), compared with expectations for a given p (assuming Gaussian approximation of MCS)
- Stopping muons are the ideal subsample for validating MCS algorithm:
 - Independent momentum measurement from calorimetry;
 - Momentum spectrum in a region of interest for future SB/LB neutrino experiments;
- Algorithm validated on ~ 400 stopping muons: produced in ν_μ CC interactions of CNGS neutrinos upstream of T600, and stopping/decaying inside the detector

Last meter of tracks not used for MCS measurement, to emulate case of escaping muons

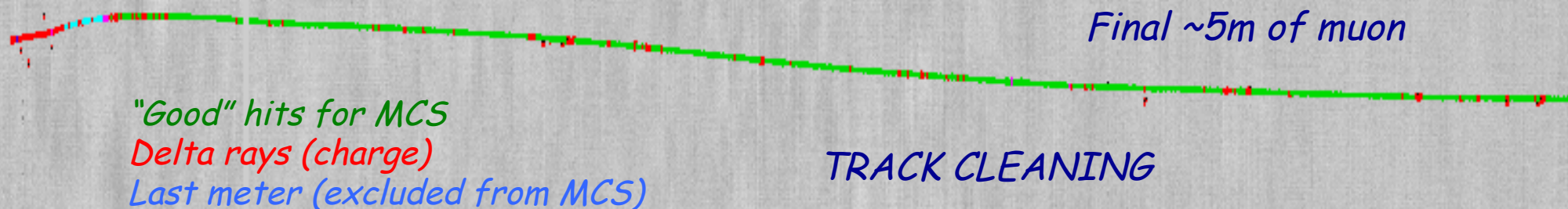
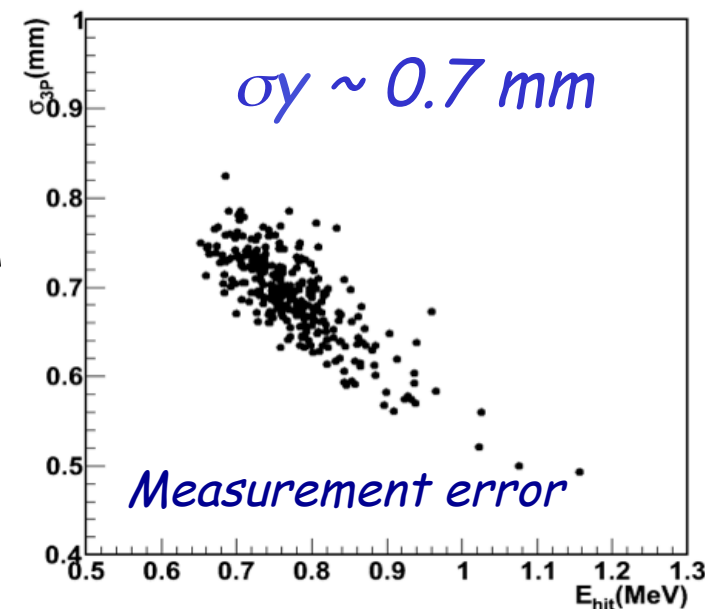


$$\theta_{RMS} \div \frac{13.6 MeV}{p} \sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$



Muon momentum measurement algorithm

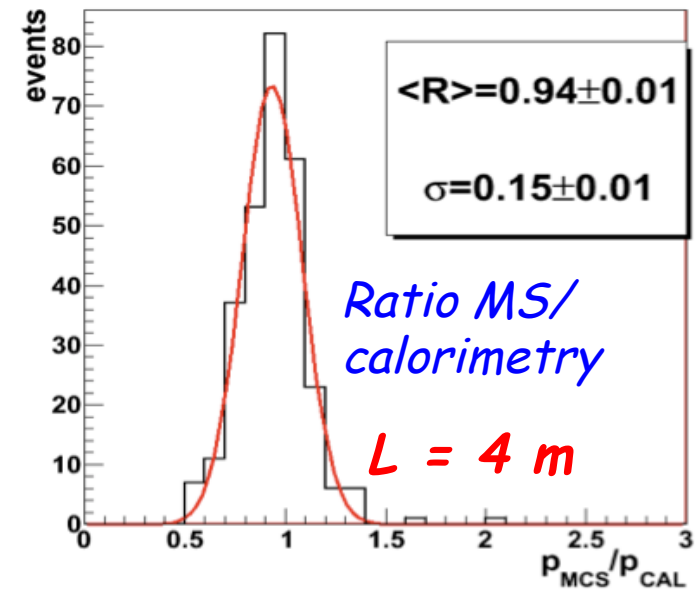
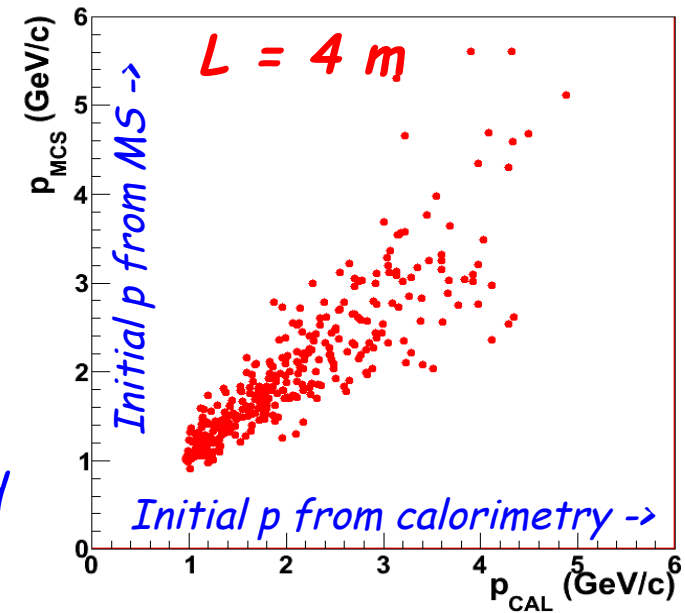
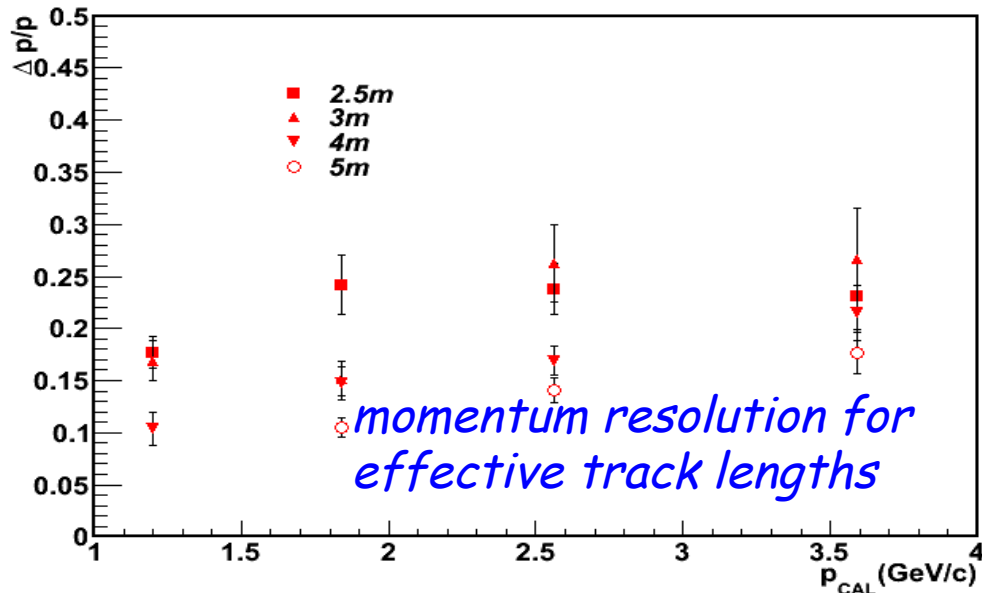
- Visual scanning for the μ identification
- 3D automatic reconstruction and visual validation of the muon track;
- Automatic track cleaning procedure, to avoid non-Gaussian tails (mainly δ -rays);
- Precise track-to-track estimation of measurement errors σ_y using the drift coordinate dispersion on short distances \sim cm to minimize MCS effect
- Track segmentation, optimized to enhance MCS contribution while reducing statistically the effect of errors
- Track deflection computed between two consecutive segments in 2D Collection view;



Muon momentum measurement results

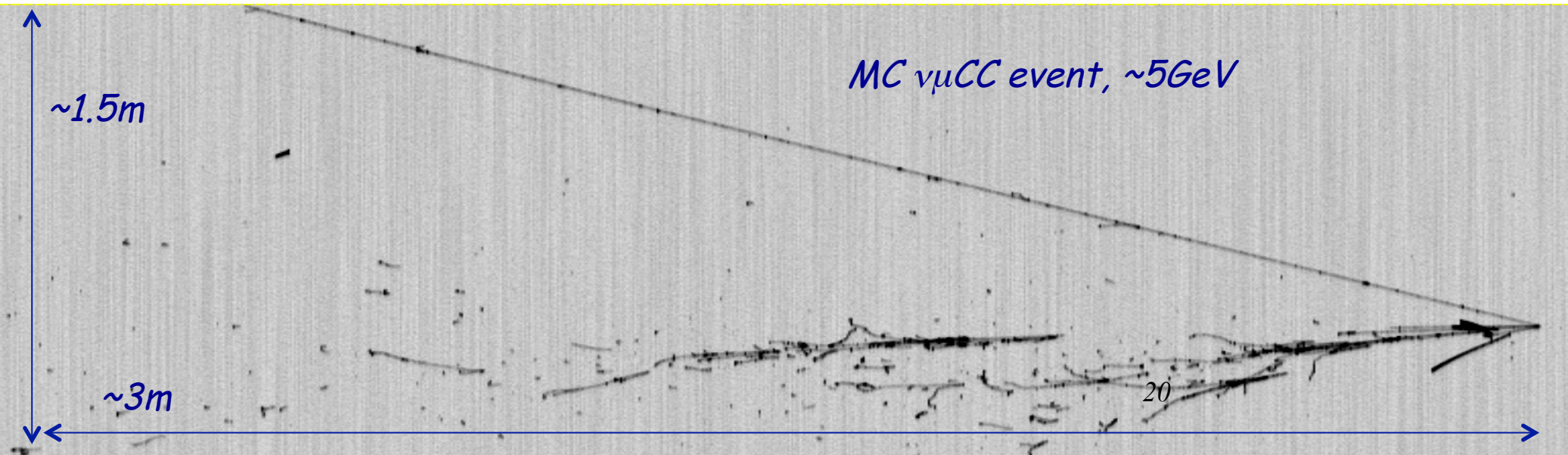
- Good agreement between MCS and calorimetric measurements
- Average resolution of $\sim 15\%$ on the stopping muon sample
- Resolution depends both on momentum and effective muon track length used for measurement

Some deviations for $p > 3.5 \text{ GeV}/c$ induced by non-perfect planarity of TPC cathode



Monte Carlo simulation with FLUKA

- Detailed and realistic MC simulation based on FLUKA
- Fortran packages provide particle transport and energy deposition in space/time cells and provide also MC vertex information;
- Fullreco classes generate signals on wires starting from the FLUKA cells and considering the known electronic response;
- All known detector effects (diffusion, electron recombination, impurities in LAr) and the electronic noise, based on measurement during LNGS, realistically simulated.



Search for ν events in CNGS beam: visual scanning

Standard processing for the events collected in CNGS spill:

- Automatic rejection of empty events;
- Visual scanning of the events by 2 different scanners and first classification in neutrino/muon from the rock/residuals;
- Visual scanning of ν candidates: event with primary vertex inside the fiducial volume (1.5 cm from detector walls, 5 cm upstream, 15 cm downstream) are classified as ν_μ CC - ν NC- ν_e candidate;
- ν_μ CC identified by $L > 2.5$ m long track without hadronic interactions;
- ν events with an e.m. shower at primary vertex are selected as ν_e cand. for further analysis

Event_Parameter

☐ Event Parameter

Event parameters

View

First Wire

First Sample

Last Wire

Last Sample

Event Type (1 = Track, 2 = Track with EM Activity, 3 = EM Shower, 4 = Neutral Interaction, 5 = Charged Interaction, 6 = Multi Muon Event, 7 = Hadronic Interaction, 8 = Muon from the Rock, 10 = Other Event Type)

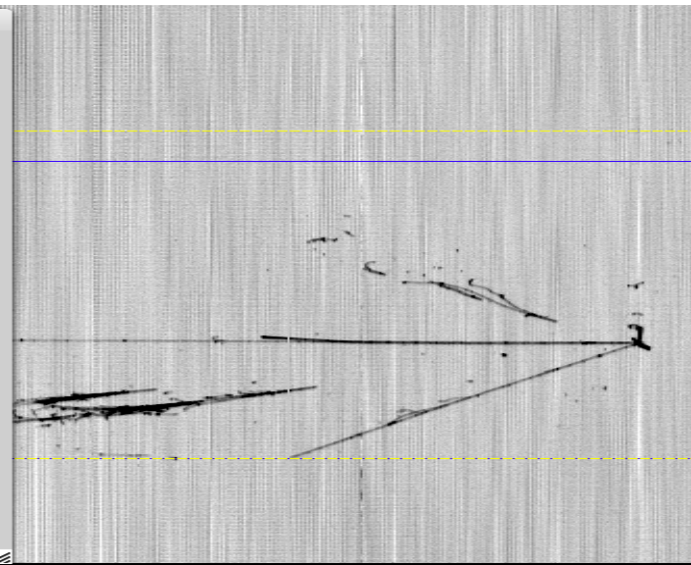
Good for Purity? (0 for NO, 1 for YES)

Noisy Event? (0 for NO, 1 for YES)

Are there staggered boards? (0 for NONE, 1 for 0-10 boards, 2 for more than 10)

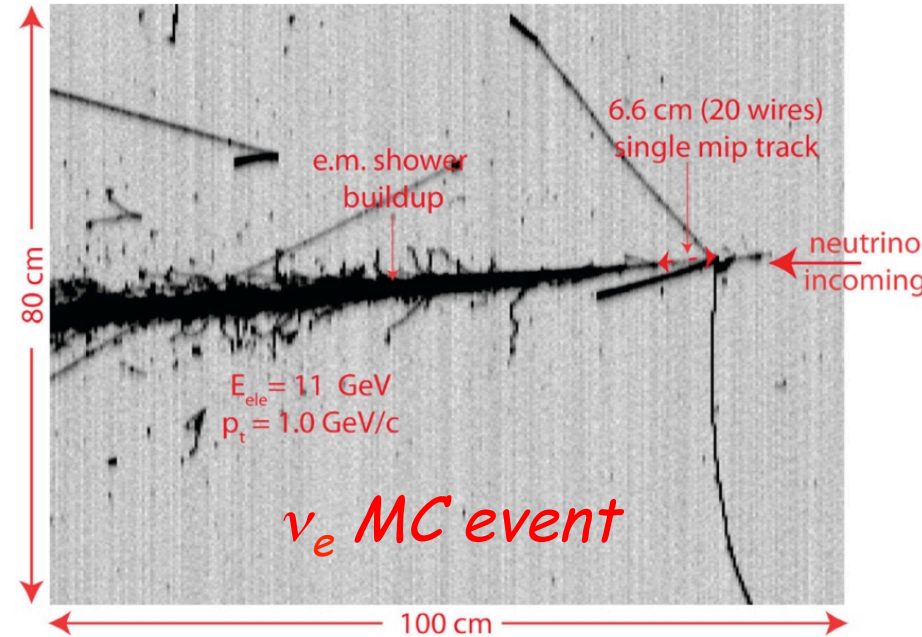
OK Cancel

Scanning window



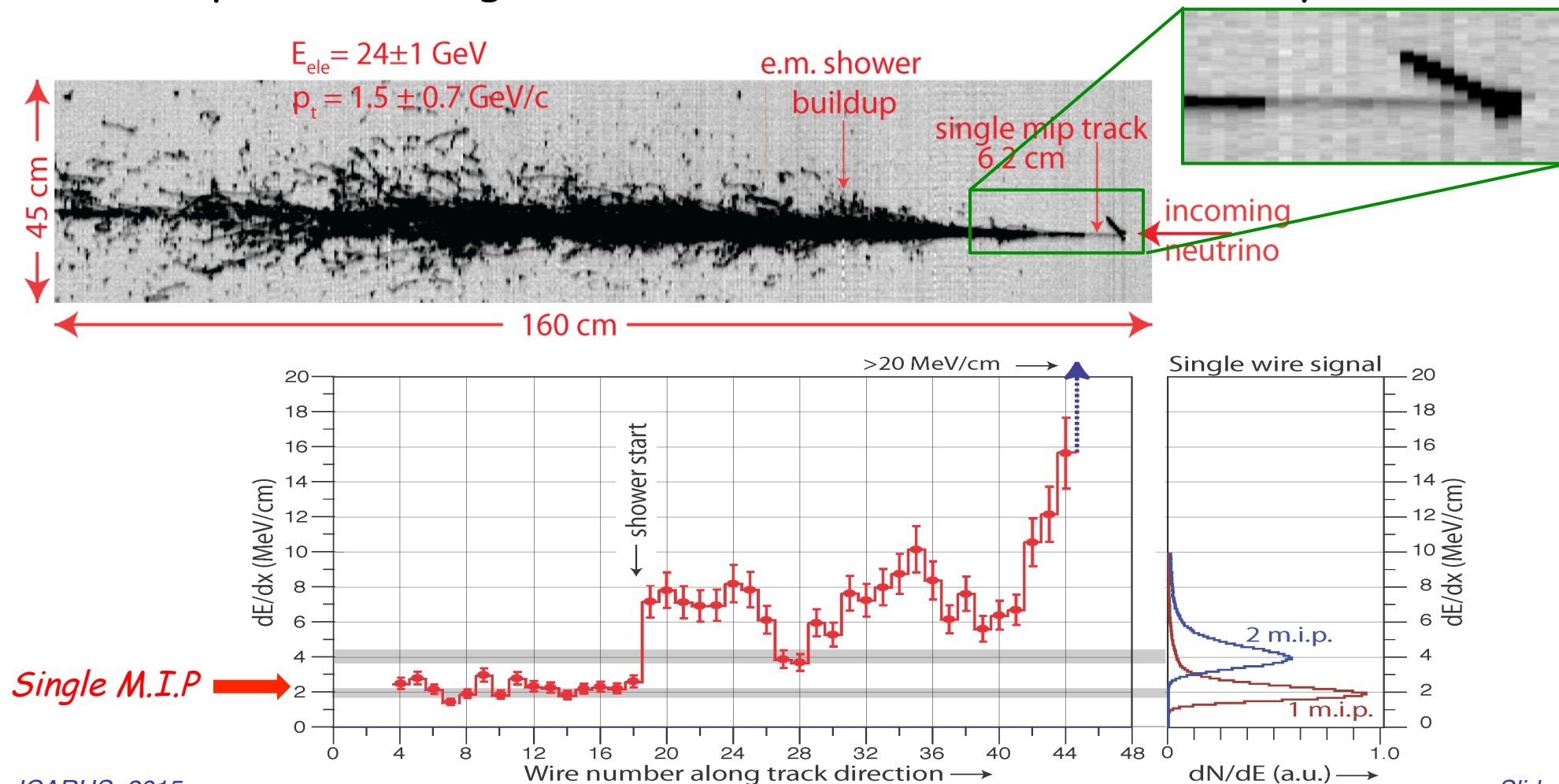
Search for ν -e events in CNGS beam

- ν_e CC candidates are visually selected with vertex inside a restricted fiducial volume (for shower id.): > 5 cm from TPC walls and 50 cm downstream
- Energy < 30 GeV
 - 50% reduction on intrinsic beam ν_e
 - only 15% signal events rejected
- The “Electron signature” requires:
 - A charged track from primary vertex, m.i.p. on at least 8 wires, subsequently building up into a shower; very dense sampling: every $0.02 X_0$;
 - Isolation (150 mrad) from other ionizing tracks near the vertex in at least one of the TPC views.
- Electron efficiency has been studied by visual scanning with events from a MC (FLUKA) reproducing in every detail the signals from wire planes: $\eta = 0.74 \pm 0.05$ ($\eta' = 0.65 \pm 0.06$ for intrinsic ν_e beam due to its harder spectrum).



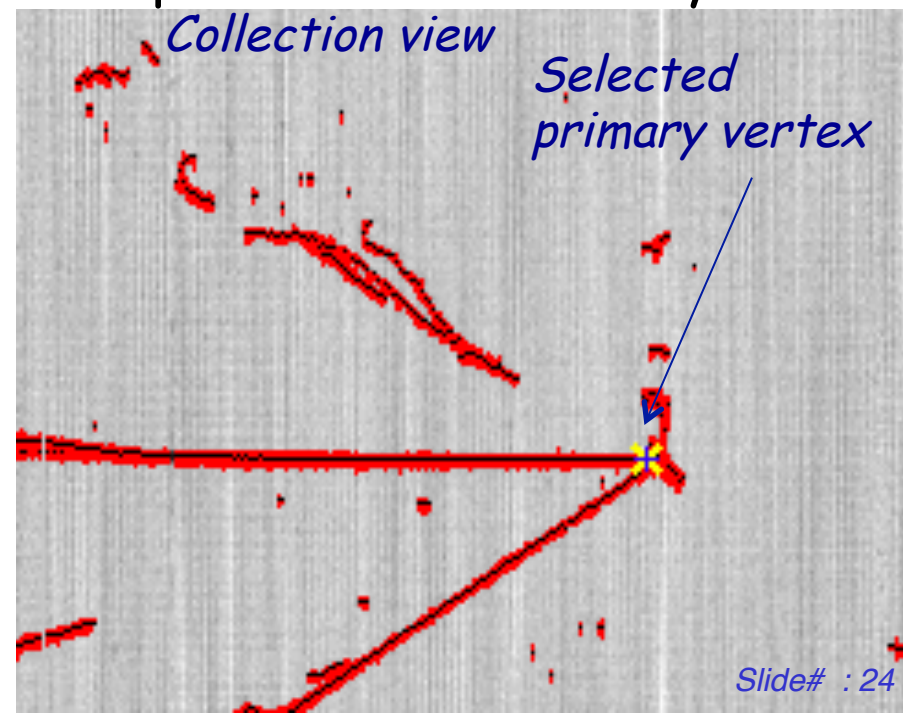
Identified electron ν interactions

- Globally 2650 ν events in the analyzed $7.93 \cdot 10^{19}$ pot (out of the fully collected statistics of $8.6 \cdot 10^{19}$ pot) studied in details to identify the electron neutrino interactions: **7 electron neutrino events identified** (8.5 ± 1.1 expected taking into account the detection efficiency)



Visual scanning for the neutrino event reconstruction

- The selected neutrino events are visually studied in details to extract all the physical information; this careful reconstruction by physicists is perfectly suitable for the number of expected events;
- Total deposited energy estimated;
- Muon cluster identified in the ν_μ CC events;
- In ν_e candidate, electron hits are grouped manually to ensure the separation between the e-shower and the hadronic activity, dE/dx at the beginning of the shower and longitudinal profile automatically reconstructed
- Manual selection of stopping particles (muons, pions, protons), to be identified by PID algorithm;
- Selection of π^0 candidate: separation of the 2 showers (if possible) to reconstruct π^0 invariant mass
- All the information stored in root files;



Conclusions

- Exposed in Gran Sasso underground Lab. to CNGS neutrino beam, the ICARUS T600 neutrino experiment with 760 ton of highly purified LAr has successfully completed a three years physics program at LNGS: 2650 neutrino interactions ($7.93 \cdot 10^{19}$ p.o.t.) have been studied in details and 7 ν_e have been identified.
- The ICARUS collaboration has developed during many years a complex system of tools for event display, scanning, reconstruction and analysis;
- Extensive T600 experience allowed us to develop, debug and tune algorithms in a real large-scale experiment environment;
- Visualization and interface with physicist are crucial functionalities for a detailed study and identification of the ν interaction and for the validation and improvements of the reconstruction;
- The relatively small number of interesting events allowed a semi-automatic approach in the analysis: while some parts of basic reconstructions are automatized, the general event classification and particle selection was left to human scanners.



Thank you !